RELIABILITY AND FUNCTIONAL AVAILABILITY OF HVAC SYSTEMS

Sonny Myrefelt
Dep. of Build. Serv. Eng., KTH, 10044 Stockholm, Sweden, and
SKANSKA Sydost, Växjö, Sweden

Summary
This paper presents a model to calculate the reliability and availability of heating, ventilation and air conditioning systems. The reliability is expressed in the terms of reliability, maintainability and decision capability. These terms are a function of the mean time between failure, mean time to repair and decision time.
The availability is expressed as an operational and functional availability of the systems. These terms are a function of both the technical and human characteristics to maintain the systems in correct operational state.
The result is based on a large amount data from operational organisations, the compulsory inspection of ventilation systems and momentary and continuous measurements made in HVAC-systems.

Keywords: HVAC-systems, reliability, availability, commissioning, building operation

INTRODUCTION

A model has been developed for estimating reliability and availability for heating, ventilation and air conditioning systems. The model makes it possible to distinguish between technical and human characteristics related to the HVAC- systems. The reliability theory forms the basis.
Of the concepts studied, the *functional availability* is judged to best reflect the overall characteristics of the technical systems and the human element.

The *reliability* is used to assess the probability that a component or a system works when no maintenance is made. A system with a high reliability thus has minimal maintenance requirements; it is a robust system.

The *decision capability* is used to assess the organisation's capacity to start carrying out remedial measures after fault detection. An organisation with typically a long time laps between fault detection and repair has a low level of decision capability.

Maintainability is used to calculate the probability that repair times will not exceed an acceptable level. Repair work usually involves the system being taken out of operation, so it is of interest to minimise repair times. Long repair times mean low maintainability.

Operational availability is used to calculate how long the system is in operation in relation to intended operating time. It mainly shows the technical capability to keep on operating while maintenance is being carried out. Systems that must be taken out of operation for longer repair works have a lower level of operational availability than others. A system with low reliability but high operational availability indicates an efficient maintenance organisation.

Functional availability is used to quantify the system's capability both to be in operation and at the same time maintain intended levels of function. This concept is judged to be the one that best and most simply shows an overall picture of the operational organisation and the HVAC-system's ability to maintain intended functions.

The study is based on a large amount of feed-back data from buildings belonging to several real estate companies. Functional availability has been given special attention as it is reckoned to be a possible base contracts of functions and how well it will be maintained. The feasibility has been tested for some buildings. The results also show that the systems are in operation during the period of use, but that the set point value is seldom maintained.

METHODS

Assumptions and conditions for the calculations of reliability and availability are associated with the intended use: study of the collected data described in the following paper.

- The systems are repairable
- The systems are subject to repair and maintenance
- The outcome of each individual repair and maintenance measure is random. This reflects a state with shortness of time and/or money, discontinuities of the work etc.
- The faults that will occur next is not known in advance
- The process is regard as a Superimposed Renewal Process
- The fault occurrence rate is constant
- The probability for fault occurrence is the same throughout the system and has a Poisson distribution
- Mean time between failures (MTBF) has been shown to have a lognormal distribution (9).
- Decision time is a variable introduced by me in this study in order to show the function of the Operation and Maintenance organisation. It is shown to have a lognormal distribution (9), which also has been assumed in the calculations.
- Mean time to repair (MTTR) is shown to have a lognormal distribution, which also has been assumed in the calculations
- That MTTR<<MTBF is shown and has been assumed when calculating the availability. Because of this the distribution of MTTR can be considered as independent

- The studied functions are assumed to be independent
- A fault is assumed to be followed by a measure, but not necessarily in direct time connection
- The system can be in a working state but not functioning
- The system is assumed to have a series connection between functions that is all function requirements have to be fulfilled.

These assumptions and conditions are the basis for the chosen expressions given below. The result is a model for calculating reliability and availability and connected factors for HVAC systems in buildings.

Failure occurrence and connected time variables

The different states associated with failure occurrence during the steady state period can be illustrated with a time axis as in figure 1.

1. The fault must be detected; this isn't always as simple as it can look.
2. The cause of the fault must be diagnosed before action.
3. The replacement must be handled or the repair must be well done.
4. At last there must be a check of the function after the measure.

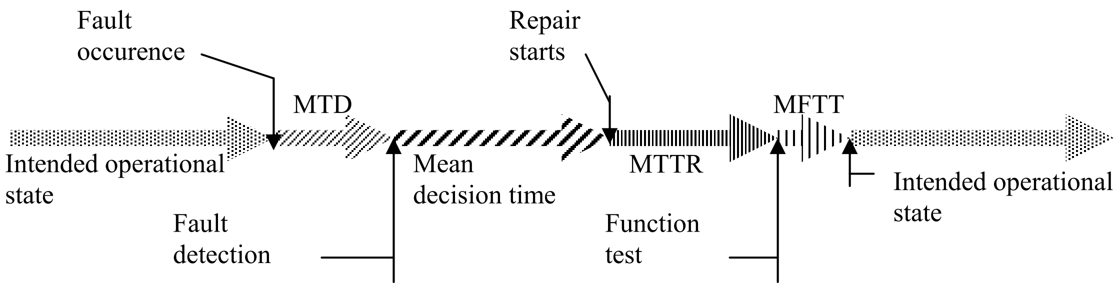


Figure 1. The different states associated with failure occurrence. The timescale isn't real.
MTD is the mean time to detect the fault. MTTR is the mean time to repair
MFTT is the mean function test time

MTBF is the mean time between failures, a measure of the cycle time illustrated in figure 2. Mean decision time is the time for diagnosing the fault, deciding which measure to take and then initiating the repair.

The time the system is repaired, i.e. MTTR, is used to calculate the *operational availability*. MTTR plus the time the system doesn't work properly, that is during MTD, mean decision time and MFTT, is used to calculate the *functional availability*.

Reliability is defined as the probability that the system (under steady state conditions) will still work at a time t, under the condition that no maintenance work has been done.
The reliability is a technical characteristic of the system, dependent on the ability of the technical solution to keep the system in operative state even though that some fault has occurred.

The mean decision time is a new variable. The decision time is the time between fault detection and start of repair. This "mean decision time" has in some works been included in mean downtime, MDT, as an administration downtime together with repair time (Kraus, J W. 1988). Since the decision time in this study is much longer than the repair time, I have chosen to separate these time variables in order to make the decision time more visible.

The values of the time variables have been collected with help by the maintenance staff in 7 different and independent building maintenance organisations. The values are given as an average from more than 5 years of 10-60 HVAC- systems per organisation. This means that the study is based on more than 100 HVAC-systems and covers over 4 000 000 operational hours.
The collection has been made with help of forms and personal visits to the organisations. One example of such a form is shown in example 1. The form is connected to the distribution system of the supply air. Since the studied systems are divided into 12 subsystems, there are 12 different forms, one for each subsystem.

Example 1. Form for: Ventilation system; supply air, distribution system

Component/ Subsystem	Operation hours/year	Number of failure/ year	Mean repair time (operation hours, o.h)	Mean time between failure detection and repair (operation hours, o.h)	Estimated level of the probability of correct repair	Note
Air inlet	6588	1				
Silencer	6588	-				
Duct	6588	-				
Damper	6588	5	0.75	20 o.h max. 1 year		From 1995 and forward this will be yearly tested
Control system to the component above	6588	20	2.5	20-30 o.h		Malfunctions in the regulator

Functional availability

Functional availability focuses on three important overall factors:

a) Characteristics of the technical systems
b) People's ability to manage and exploit the characteristics
c) Balance between the target formulations and the technical system chosen

Each phase in a building project includes items and solutions that affect these factors. Incorrectly chosen solutions or incorrect design provides a basis that generates low functional availability. Such projects can normally not be dealt with by anything less than comprehensive rebuilding.

Components with a high tendency for faults in combination with low observability also provide a basis for low functional availability.

The potential and ability of operating personnel to perceive emerging faults and to deal with them is naturally extremely important for the level of functional availability.

In order to be able to quantify the functional availability, basic target formulations must be set. The target formulations must be characterised by being:

1. Intelligible
2. Observerable
3. Open to influence
4. Representative
5. Measurable
6. Distinctive

Overall functions such as good air quality are still often too vague to be used as a target formulation. There is no good measure of it. Since this is the case, the design airflow rate often is used as a target formulation connected to the ventilation system. This value doesn't give any answer of the air quality in the room, it only gives a value if the desired air flow rate is maintained.
Target formulations must be set up early in the project and remain during the whole process including the operation phase. As the basis for target formulations, specifications are produced by interest groups and authorities (14).

In this paper two field studies of a proposed method of evaluation of the functional availability of a climate installation are presented and discussed.

Functional availability based on momentary measurements

The airflow rates were collected from the compulsory inspection forms of 375 ventilation systems (8). The other operational condition variables were measured in 44 independent ventilation systems and in 188 office rooms connected to the 44 ventilation systems. All the ventilation systems were designed to also handle comfort cooling.
The measurements were taken in springtime, April, and the outdoor temperatures were almost all the time below 15 °C.

The results from the studies (8, 9) were based on the supply air temperature not exceeding 20°C during the heating season, and during the cooling period not below 15°C. Where there were specified targets, these were used.

The airflow rate is normally easy to measure. Recommended measuring methods have been published by Nordiska Ventilationsgruppen (10). How to document adjusted and measured airflow rates is included when preparing building contracts. For each ventilation system, therefore, there must be sufficient documentation of design airflow rates.
The compulsory ventilation checks performed in Sweden have focused on the importance of maintaining the design air flow rates. More about this activity can be seen on www.funkis.se.
Faults in the airflow rate can normally be traced to

a) Control and operating systems
b) Adjustment
c) Design

Faults in the heat supply to the room are not normally shown by computerised monitoring systems. Temperature detection in the rooms in combination with detection of the heater's temperature is not normally included. The method used in this study was to compare the radiator temperature with the room air temperature. If the radiator temperature was higher than the room temperature and the room temperature was higher than the set point it would be considered as a fault (8).

Functional availability based on continuous measurements

The criteria is that the desired functions should be maintained during working time. The time when there is no deviation between the desired criteria and the actual value is used to calculate the functional availability. This can be written as

$$A^*_i = \frac{t_f}{t_{wt}} \qquad (1)$$

A^*_i is the functional availability of function i
t_f is the summarised time with no deviation (h)
t_{wt} is the summarised time when the functions should be maintained (h)

In systems where several target formulations are studied, the combined functional availability can be estimated according to equation (16).

Calculation example: Study of room temperature in an office call-centre

The basis for this calculation example was obtained from field measurements in an office in the southeast of Sweden. The measurement period was very short and has been used only in order to have a simple example.
The tenant complained about varying room temperature.
The following operating conditions and target formulation for the room temperature applied to the project:

Operating time	24 h/day
Room temperature	> 21 °C during the winter period

The heating system consisted of heaters in each room and the heaters are equipped with electronic valves which were connected to the control system. The cooling device in the room is was an air supply baffle which was connected to both the ventilation system and to a hydraulic cooling system.

The measured data in this study covers a total of 47 hours. Room temperature and time are shown in figure 2. Data as per table 1 can be produced from figure 2.

Table 1. Number of minutes (out of a total of 47 hours) during which the temperature fell below the specified requirement of 21 °C

Period	**Room B102:1**	**Room B102:2**	**Room B103**	**Room B104**
17- 19 January	0	2409	1830	1494

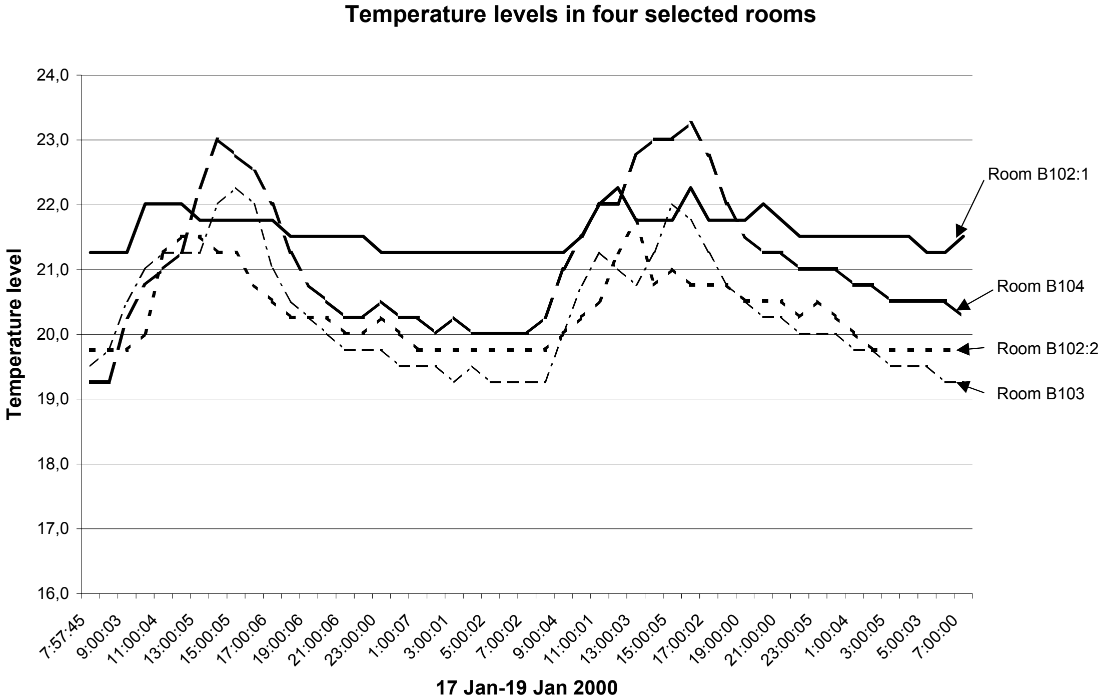


Figure 2. Measured data for the room temperature in four rooms during the period 17/1 -19/1. The measuring period covers a total of 47 hours.

The functional availability of room temperature in room B102:2 is calculated with help from equation (1) as follows

$$A^{*}_{B102:2} = 1 - \frac{2409}{2820} = 0.15$$

Table 2. Functional availability for each room calculated for the period 17-19/1.

Period	**Room B102:1**	**Room B102:2**	**Room B103**	**Room B104**
17/1-19/1	1	0.15	0.35	0.47

The total functional availability for the *system of the four rooms* will then be, see equation (16):

$$Af^{*}_{sys} = \frac{1}{1+\frac{1-1}{1}+\frac{1-0.15}{0.15}+\frac{1-0.35}{0.35}+\frac{1-0.47}{0.47}} = 0.10$$

The functional availability of room temperature for the rooms studied, was very low during the experiment. However, it must be considered that the function criteria were narrow. (Feasibility of function criteria was not part of the study.) There are currently no values for what should be considered acceptable levels for functional availability. Reasonable levels should be above 0.8, in my opinion. Since there has been complaints by the users a functional availability of 0.10 obviously is to small to be accepted

From the data, it is clear that during the observed period no measures were taken to rectify the problems. On the other hand, detection of the fault has taken place, which means that the period can be classified as decision time.

The observed period is short but in reality the fault has been present for a long period, probably more than 2 months. It is recommended that the measurements is taken over a longer period. The cause of the faulty condition such as

- low air supply temperature
- high air supply rate
- fault in the heating system
- fault in the control system

have not been part of the study.

RESULTS

The results, using the model to evaluate the data collected in this study, are discussed under the following headline:

- The reliability of the systems
- The maintainability of the systems
- The decision capability of the maintenance staff
- The operational availability of the systems
- The functional availability of the systems

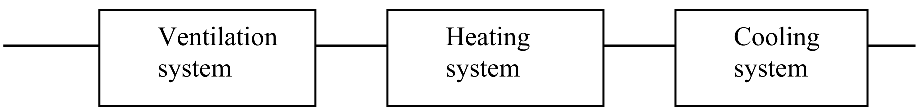
The first four depend only on the time variables, and functional availability, also on the operational condition variables.

The functional availability results are of course strongly dependent on the function criteria. The data collected in this study were mostly based on criteria not actively chosen but already in use for the buildings. The function criteria for the supply air flow rate was simply if it was accepted or not in the OVK (the compulsory inspection of ventilation system). Temperatures should be ± 1 °C around the set point value, which is a tough condition, and perhaps too narrow for a control strategy taking building heat accumulation into account. This indicates that the functional availability results of the study may be biased, giving too low values. The result is most interesting, however, but should be read with the possible bias in mind.
Study of the feasibility of different function criteria was not been part of this study.

The Reliability of the Systems

Reliability is defined as *the probability that the system (under steady state conditions) will still work at a time t, with no maintenance work done*.

This means that the system starts at a time $t=t_1$ and no maintenance will be done during the studied period. The subsystems of the total system are assumed to be independent and connected in series to each other. This can be shown as follow.



A fault in one of the subsystems may occur and then implies a fault in the HVAC-system. A measure should be done but is not. This doesn't necessarily imply that the system must stop. The reliability takes this into account, as it is the probability that the system will still be in operational state after a time *t*.

The reliability is a function of the number of components that can fail. More components give in most cases a lower reliability.
The reliability is a technical characteristic of the system, dependent on the ability of the technical solution to keep the system in operative state despite the fact that some fault has occurred

The results from the studies of the reliability of the total systems are shown in figure 3. The total system consists of the heating system, the cooling system, the ventilation system and the part of the control system, which is connected to each of the other systems.

Example 2. This example corresponds to figure 3. The reliability after 1000 operational hours differs greatly between the systems. The system in organisation 6 has the lowest reliability, about 0.05 and organisation 4 the highest, about 0.7. This indicates that the maintenance staffs have to be more available in organisation 6, if the owner wants to keep the system in an acceptable operational state.

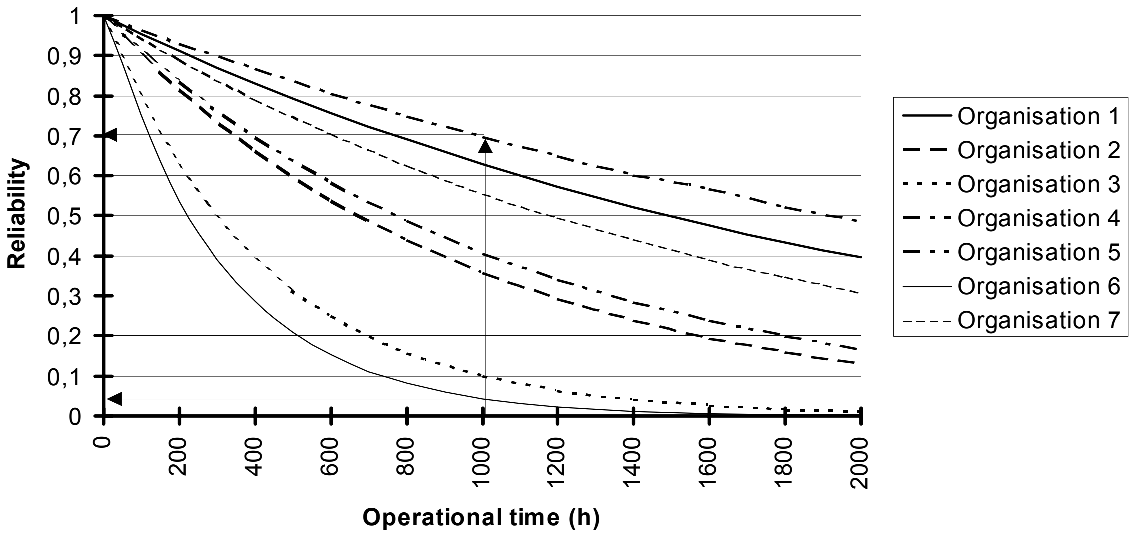


Figure 3. The reliability as a function of the operational time for seven studied organisations. See example 2 for explanations of the arrow at operational time 1000 h.

The reliability of each of the subsystems, ventilation, heating and cooling, as well as for the total system, is calculated as an average of the seven studied organisations and is shown in figure 4.

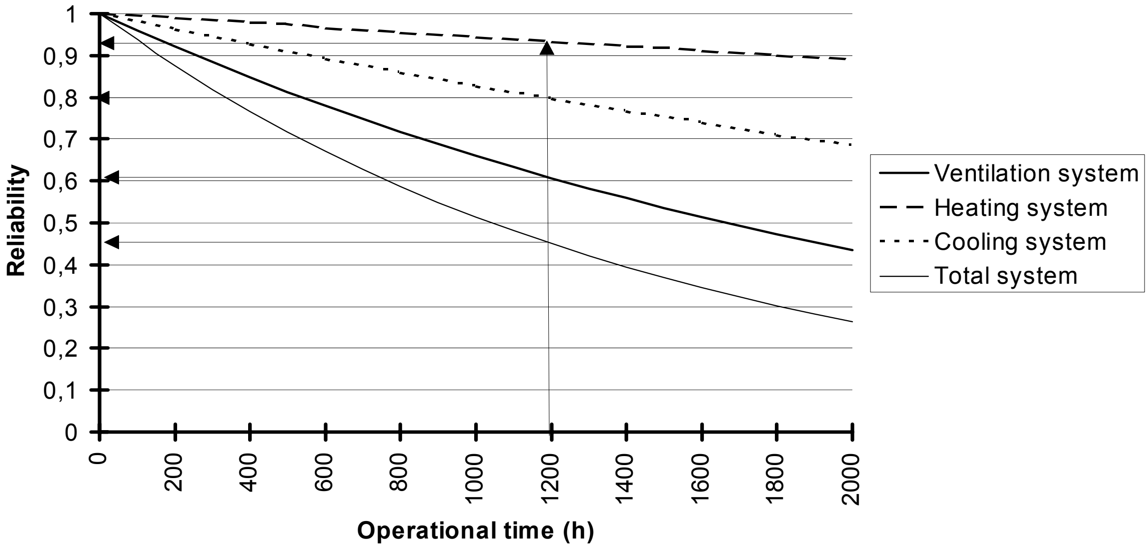


Figure 4. The reliability of the ventilation system, the heating system and the cooling system as an average of the studied systems. In the figure arrows show the reliability at 1200 operational hours.

The ventilation system has the lowest reliability of the systems. This indicates that there are more failures in the ventilation systems than in the others.

The Maintainability of the Systems

The maintainability is *the probability that the repair time is less than an "allowed" time*. This means that the cumulative distribution function of the distribution of repair times evaluated at t_r (13)

$$M(t_r) \equiv \int_0^{t_r} g(x)dx \qquad (2)$$

The function $g(x)$ is the probability density function of repair time which has been showed to be log-normal (9).

The repair time is the time from the start of the measure/repair to start of the system again. Repair time doesn't include administration time.
The maintainability is dependent on both technical characteristics and the knowledge and experiences of the maintenance staff.

The maintainability of the total system for the seven studied organisations is shown in figure 5.

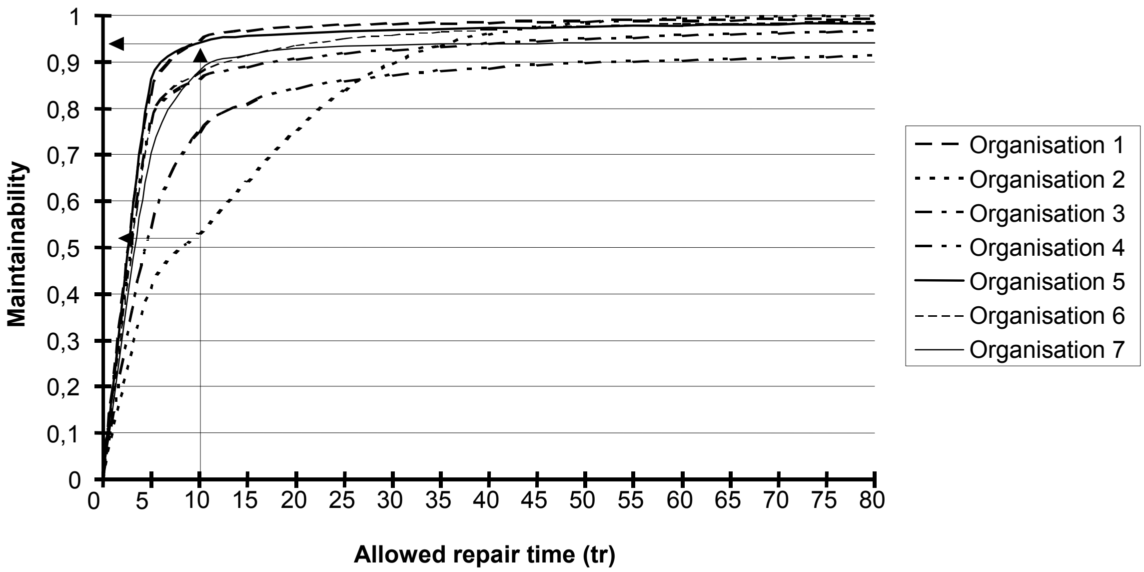


Figure 5. The maintainability (that is the probability that the repair time is less than an "allowed" time) of the total system for seven studied organisations.

With an allowed repair time of 10 operational hours the maintainability of the total system differs from 0.52 (organisation 2) to 0.95 (organisations 5 and 1). Evidently there is quite a difference in repair time of the systems. A system with a long repair time cannot be in operational state as quickly as the other systems. The repair time depends not only on the technical systems but also on the maintenance staff or the contractor. Differences between the organisations regarding the maintenance staff influence the results.

The results for each system, i.e. the ventilation, the heating and the cooling systems, which are shown in figure 6, show obvious differences.
The result indicates that the repair time of ventilation systems is much less than that of the other systems. If we compare the reliability of the systems, see figure 4, the following conclusions can be made:

- The ventilation system has a high frequency of failures but it takes a short time to repair those failures.
- The heating system has a low frequency of failures but it takes a long time to repair the failures.
- The cooling system lies between the two other systems but it seems to behave more like a heating system than a ventilation system.

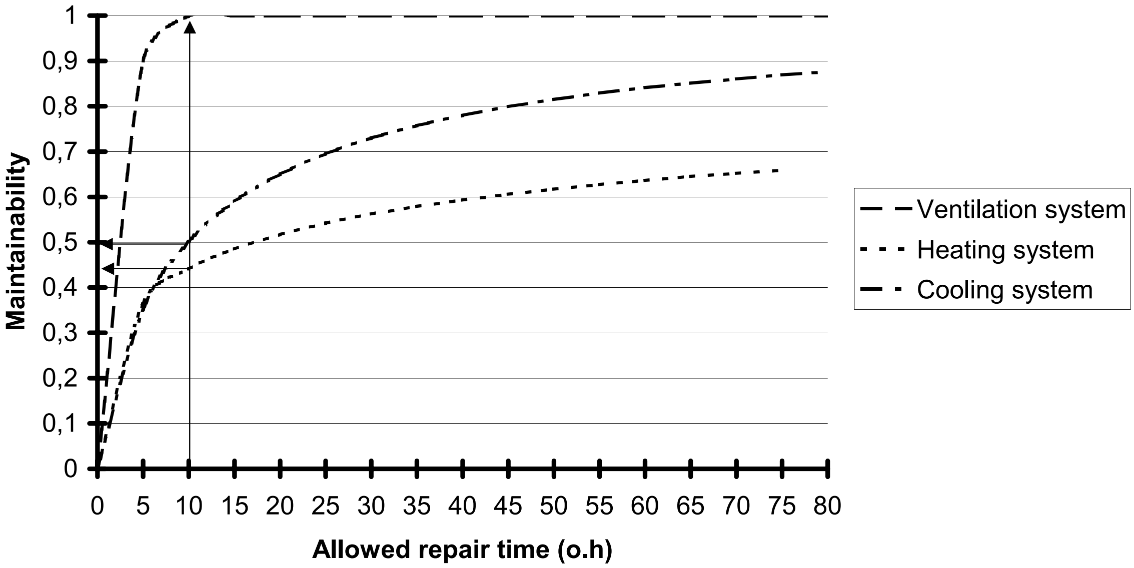


Figure 6. The maintainability of each system as an average of seven studied organisations.

The Decision Capability of the Maintenance Staff

Decision capability is *the probability that the decision time t_A (the time between failure detection and start of measure/repair) is equal to or less than an "allowed" time, t_a.*
This means the cumulative distribution function of the distribution of decision time evaluated at t_a.

$$D(t_a) \equiv \int_0^{t_a} f(t)dt \qquad (3)$$

The function $f(t)$ is the probability density function of decision time which has been shown to be log-normal (9). The decision time isn't as visible in the reliability theory (5, 7, 11) as in my study probably because this time is very short compared to repair time in many applications. This is not valid for HVAC-system because many HVAC systems are in operational state without maintaining the specified function levels
The decision time is independent of the technical solutions; it is just a characteristic of the administration.

The decision capabilities of the maintenance staffs for the total systems are shown in figure 7.

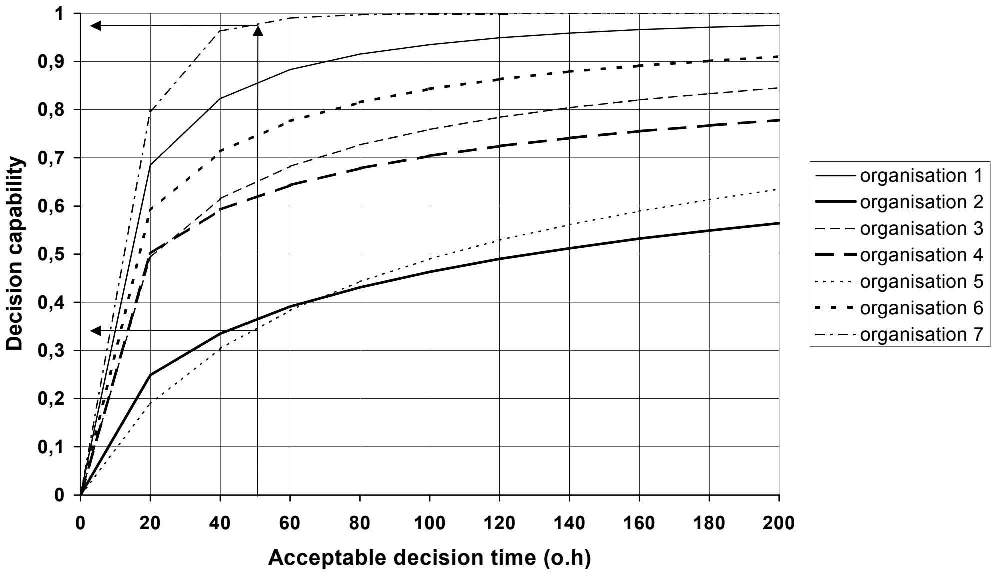


Figure 7. The decision capability of the maintenance staff for the total HVAC-systems.

The differences between the organisations are evident. With an assumed allowed decision time of 50 operational hours the lowest decision capability is 0.34 (organisation 5) and the highest is 0.98 (organisation 7), see the arrows in figure 7.
The decision capability of the maintenance staff, as an average of the studied organisations, is shown in figure 8.

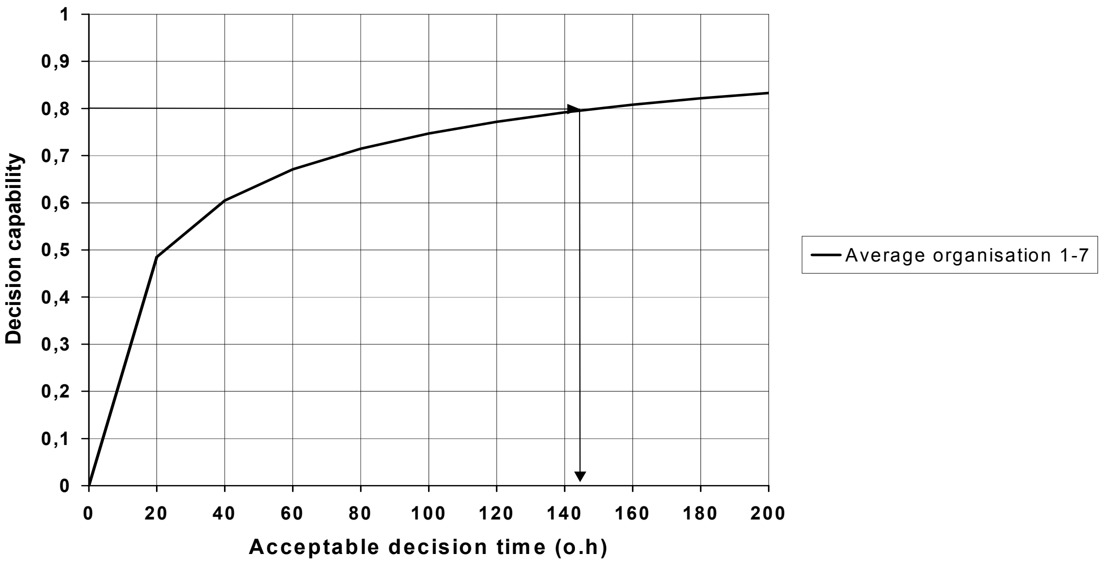


Figure 8. The decision capability of the maintenance staff as an average of the studied organisations.

If we want to reach a decision capability of 0.8 we have to accept a decision time of 140 operational hours. This is almost 20 times longer than the repair time at the same probability, see figure 5.

The results presented in figure 8 indicate that the systems are in faulty operational conditions for a long time. The staffs have detected the failure but “nothing” is done to repair it. The causes of this can vary.

The Operational Availability of the Systems

The operational availability is *the probability that the system will be in the intended operational state*. In contrast to system reliability it takes maintenance into account.

The function criteria such as room temperature are not connected to operational availability in this case. It means primarily that the central heating plant or the central cooling plant is in operational state. This means that if the “conventional maintenance” is well-done and if the technical components have a high reliability, the operational availability will be high.

The result of the operational availability with data from the seven organisations is shown in table 3.

Table 3. The operational availability of the studied systems.

Organisation	**Operational availability**			
	Ventilation system	Heating system	Cooling system	Total system
1	0.999	0.999		0.998
2	0.999	1	0.986	0.985
3	0.996	1	0.988	0.984
4	0.999	0.978	0.999	0.976
5	0.999	1	0.998	0.997
6	0.998	1	0.994	0.992
7	0.998	1		0.998
Average	0.998	0.997	0.993	0.990

The operational availability is almost 1.0, as can be seen in table 3. This indicates that the system downtime is short or is not frequent enough to affect the operational availability. This implies that the system components have been developed in accordance with their intended use and that *the maintenance is well done*.

The Functional Availability of the Systems

The operational condition variables which have been used in this study are

- Supply air temperature
- Air flow rate
- Heating system function

These variables have been selected because they are representative for the performance of the system. The probability calculation is based upon momentary measurements connected to randomised rooms in several buildings (8, 9). There are others variables that could be included but the study is principally a test of the model.

The measurements are independent of the operational availability because the measurements are done when the system is operating. We can therefore use the product rule of probabilities. The functional availability $A^*(\infty)$ can then be calculated as

$$A^*(\infty) = A_i(\infty) \cdot \prod_{i=1}^{n} p_i \qquad (3)$$

$A_i(\infty)$ is the operational availability of system number i

p_i is the probability of correct value of the operational condition variable number *i*.

The results from these studies (8) showed that for the tested buildings the probability

1) to maintain the designed supply air temperature was 0.30

2) to maintain the designed air flow rate was 0.59
3) to maintain the intended heat supply was 0.48

If we use the number from the above mentioned studies the following calculation of the functional availability can be made, see equation (16).

$$A^{*}{}_{f,sys} = \frac{1}{1+\frac{1-0.30}{0.30}+\frac{1-0.59}{0.59}+\frac{1-0,48}{0.48}} = 0.20$$

The result indicated a low functional availability which of course depends on the used number of “the correct value”. With another level of “the correct value”, that is not so tough, the functional availability would be higher. In this paper the aim is to show how to use and calculate the functional availability.

DISCUSSION

General indications of the study of collected data

- The *operational availability is high*, almost 100%
- The *functional availability of the systems seem to be low*, mainly because of malfunction of the ventilation system. However, the function criteria need more study to ensure that they are feasible,
- The *decision time* of the maintenance staff is long compared to the repair t*ime*
- The *system reliability* depends strongly on the technical solution and the number of
- components
- There are big *differences between the organisations*

The good operational availability shows that the *ordinary maintenance is excellent* and that the subsystems contain well-known components and equipment.
In contrast to this the *functional availability* indicates that the maintenance staff perhaps didn’t manage to handle the functions connected to the systems. This leads to difficulties in maintaining a good indoor climate and at the same time minimizing energy use.

The decision time is much longer than the repair time. This can mean that the maintenance staff takes a long time before repair or other action, or that one has to wait for delivery of components for exchange. Another cause is that lack of funding prevents any action being taken. I haven’t gone further in this study with the last points.

When the measure has been decided it takes a short time to repair and this is satisfactory.

The differences in the calculated reliability between the organisations depend largely on the number of components in the system. Some of the systems include a component that is damaged frequently. This of course influence the result.

The differences between the organisations are probably caused by both the technical solutions and the characteristics of the organisation itself.

The model used is valid when a state of equilibrium (that is “business as usual”) has been achieved, which is why short time studies should be avoided. There must also be a reasonable possibility of repairing/correcting any fault.

The Future

Using automatic registration of time and measured values, deviations from the set point values can be documented and used to calculate the systems functional availability and the tendency for faults.

From the studies shown, it is clear that functional availability can form an overall quantification of how well functions can be maintained. This can be used for quality assurance of the operation and maintenance organisation’s work, and can form a basis upon which performance procurement can be agreed.

All target formulations linked to time registration and measured values can be used for the calculation. Each target formulation is documented separately. In this way, it is possible to start from the overall combined functional availability and from there search for the area within which the fault has occurred. This could be combined with a FDD system.

The functional availability provides

a) A combined overall assessment of several target formulations
b) A level of functional availability calculated for each individual target
c) An option to look for which function is failing
d) An option to specify an overall requirement for performance based contracts
e) An option to provide a total quantification of functions purchased

The model can, if automatic documentation of the variables is developed, be an instrument to use in connection with

a) Contracts based on system performance and building function
b) Wage contracts for the maintenance staff
c) Making a data base supporting choice of technical solutions
d) Developing new components and systems
e) How to choose the characteristics of the organisation
f) A computerized control monitoring system

Function criteria should be studied in the future, especially their connection to energy use and to robustness of the systems. Also, the dependence of functional availability on the chosen criteria should be studied for several systems.

NOMENCLATURE AND MATHEMATICAL EQUATIONS

The mathematical equations and theory is taken from standard literature in mathematical statistic , probability theory and reliability theory (1, 5, 6, 11, 13).

Equations of reliability

The reliability is calculated as *the probability that the system (under steady state conditions) will still work at a time t, under the condition that no maintenance work has been done.*
Of course, for the continuous function of the system, the need to have preventive maintenance is evident.

Consequently, I have only studied the failures that can be assumed to be independent of the preventive maintenance.

The reliability of a *component* is calculated as

$$R(t) = e^{-\lambda t} \qquad (4)$$

λ is the constant failure rate of the component [h^{-1}]
t is the operational hour (o.h)

The reliability of a *series system* is calculated in the same way. We just have to calculate the mean time between failures of the system, $\overline{\Delta t}_{F,sys}$. To calculate the mean time between failures of the system we use the failure characteristics as follows

$$\overline{\Delta t}_{F,sys} = \frac{1}{\lambda_{sys}} = \frac{1}{\sum_{i=1}^{n} \lambda_i} = \frac{1}{\sum_{i=1}^{n} \frac{1}{\overline{\Delta t}_{F,i}}} \qquad (5)$$

$\overline{\Delta t}_{F,sys}$ is the mean time between failures (MTBF) of the system, operational hours (o.h)
$\overline{\Delta t}_{F,i}$ is the mean time between failures (MTBF) of system *i*. (o.h)
λ_{sys} is the failure rate (ROCOF) of the system, (number/o.h)
λ_i is the failure rate (ROCOF) of system *i*. (number/o.h)

This can be done because the failure occurrences are regarded as random and independent of each other. Division is made in subsystems, which are independent of each other.

The reliability of the system is then calculated as

$$R_{sys}(t) = e^{-\lambda_{sys} t} \qquad (6)$$

Equations of Maintainability

The maintainability is quantified as
The probability that the repair time is equal to or less than an "allowed" time, t_r.

The "allowed" repair time can be used as an aim to reach and is then a part of the maintenance staff policy document.

The repair time is shown to have a lognormal distribution (9).
The maintainability of subsystem i is then calculated as

$$M_i(t_r) = \Phi\left[\frac{1}{s}\ln\left(\frac{t_r}{t_R}\right)\right] \qquad (7)$$

$\Phi[\ ]$ is the standardised normal distribution
s is the standard deviation of the logarithmic repair time
t_r is the "allowed" repair time [o.h]
$\bar{t}_{R,i}$ is the mean repair time of subsystem i [o.h]

Since the system consists of numerous components, each with an individual failure rate, we have to take into account the frequency of each component's failure. This is done with the probability of occurrence, which is calculated as

$$P_i = \frac{\overline{\Delta t}_{F,sys}}{\overline{\Delta t}_{F,i}} \qquad (8)$$

The maintainability of the system can then be calculated as

$$M_{sys}(t_r) = \sum_{i=1}^{n} \frac{\overline{\Delta t}_{F,sys}}{\overline{\Delta t}_{F,i}} M_i(t_r) \qquad (9)$$

$M_i(t_r)$ is calculated from equation (7).

Equations of Decision Capability

The decision capability of the maintenance staff is quantified as
The probability that the decision time t_A (the time between failure detection and start of repair, see figure 2), is equal to or less than an "allowed" decision time, t_a.

The decision capability is calculated in the same way as the maintainability. The decision time is also shown to have a lognormal distribution (9).

The decision capability of the maintenance staff of a subsystem then is calculated as

$$D_i(t_a) = \Phi\left[\frac{1}{s}\ln\left(\frac{t_a}{t_{A,i}}\right)\right] \qquad (10)$$

$\Phi[\ ]$ is the standardised normal distribution

s is the standard deviation of the logarithmic decision time
t_a is the "allowed" decision time [o.h]
$t_{A,i}$ is the mean decision time of system i [o.h]

The decision capability of the maintenance staff of the total system is calculated as

$$D_{sys}(t_a) = \sum_{i=1}^{n} \frac{\overline{\Delta t}_{F,sys}}{\overline{\Delta t}_{F,i}} D_i(t_a) \qquad (11)$$

$D_i(t_a)$ is the decision capability of the maintenance staff of subsystem number i, calculated from equation (10)

Equations of Operational Availability

The operational availability of the systems is quantified as
The probability that the system will be in the intended operational state.

This means that the operational availability is a function of the downtime caused by the repair time and the time of preventive maintenance.
The operational availability of a component is calculated as

$$A(\infty) = \frac{\overline{\Delta t_F}}{\overline{\Delta t_F} + \overline{t_R}} \qquad (12)$$

$A(\infty)$ is the operational availability when steady state can be assumed
$\overline{t_R}$ is the mean repair time of the component (o.h)

The operational availability of the system is calculated similarly.

The mean repair time of the system is calculated with regard to the frequency of each repair type as follows

$$\bar{t}_{R,sys} = \sum_{i=1}^{n} \frac{\overline{\Delta t}_{F,sys}}{\overline{\Delta t}_{F,i}} \bar{t}_{R,i} \qquad (13)$$

The operational availability of the system in steady state can then be calculated as

$$A_{sys}(\infty) = \frac{\overline{\Delta t}_{F,sys}}{\overline{\Delta t}_{F,sys} + \bar{t}_{R,sys}} \qquad (14)$$

If a system consists of more than one subsystem such as heating system, ventilation system and cooling system the availability of the total system can be calculated as follows

$$A_{sys}(\infty) = \frac{1}{1 + \sum_{i=1}^{n} \frac{1 - A_{sys,i}(\infty)}{A_{sys,i}(\infty)}} \qquad (15)$$

$A_{sys,i}(\infty)$ is the operational availability of system number i.

The calculation is carried out in several steps because the functional availability of each subsystem is valuable to show as a base to failure searching when it appears.
Another view is that when a subsystem is down the others also are down and the risk of failure doesn't exist until it has been repaired.

Equations of Functional Availability

The functional availability is a product of the operational availability and *the probability that the system will be in operational state with correct values of the operational condition variables.*

The functional availability can be expressed as a probability of maintaining each target formulation but it can also be included in a general assessment of several target formulations. It is best to keep underlying target formulations separate, otherwise comparisons between levels of functional availability may be misleading.

The functional availability is calculated and designated in the previous example as a function of supply air temperature, heat supply and room temperature.

$$A^*_{f,sys} = \frac{1}{1 + \sum \frac{1 - A^*_i}{A^*_i}} \qquad (16)$$

A^*_i *is the functional availability of function i*

REFERENCES

1. **Ascher, H, & Feingold, H**. Repairable Systems Reliability: Modelling, Inference, Misconceptions and their causes. New York: Marcel Dekker, Inc. (1984).

2. **ASHRAE Handbook Application**. Chapter 38: Operation and maintenance management. ASHRAE Inc. 1791 Tullie Circle, N.E., Atlanta, USA. 2003.

3. **ASHRAE Handbook Applications.**. Chapter 37, Operation and maintenance management. ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA 30329. 1999.

4. **Hale Jr. Peyton S and Arno, Robert G**. Survey of reliability and availability information for power distribution, power generation, and HVAC components for commercial, industrial, and utility installations. New York. ASHRAE Transaction, Research. 2001. V 107 part 2, page 360-389.

5. **Ireson, W.G. & Coombs, C.F. (Red.).** Handbook of Reliability Engineering and Management. Chapter 19. Mathematical and statistical methods and models in reliability and life studies. New York: McGraw-Hill Book Company. 1988.

6. **Kraus, John, W**. Maintainability and reliability. Chapter 15 of Handbook of Reliability Engineering and Management. Ireson, W.G & Coombs, C.F. (Red.). New York: McGraw-Hill Book Company. 1988.

7. **Lewis, E.E.** Introduction to reliability engineering. New York: John Wiley & Sons, Inc. 1987.

8. **Myrefelt, S.** Modell för erfarenhetsåterföring av driftsäkerheten i klimat- och ventilationssystem. (Model for experience feedback of the reliability of climate and ventilation systems) Kungliga Tekniska Högskolan, Installationsteknik. 1996. Report no. 41.

9. **Myrefelt, S.** The reliability and availability of heating, ventilation and air conditioning systems. Submitted to Energy and Building – REHVA Scientific. 2003.

10. **Nordiska Ventilationsgruppen 1992**. Metoder för bestämning av luftflöden i ventilationsinstallationer. Statens institut för byggnadsforskning.

11. **O'Connor, P.D.T.** Practical reliability engineering (3 edition). New York: John Wiley & Sons. 1994.

12. **Ruud, Svein.** Fault detection method. Stockholm. Royal Institute of Technology, Building services engineering. Sweden. 1997.

13. **Sherwin, D.J. and Bossche, A.** The reliability, availability and productiveness of systems. Chapman & Hall, London, United Kingdom. 1993.

14. **Olesen, Bjarne.** ASHRAE Journal, August, 2000. Guidelines for comfort. ASHRAE Inc. 1791 Tullie Circle N.E. Atlanta, GA 30329. USA.